

Production of strange particles at intermediate p_T at RHIC

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Abstract

The recombination model is applied to the production of K , ϕ , Λ and Ω at all p_T in central Au+Au collisions. The thermal-shower component of the recombination is found to be important for K and Λ , but only in a minor way for ϕ and Ω in the intermediate to high p_T region. The normalization and inverse slope of the thermal partons in the strange sector are determined by fitting the low- p_T data. At higher p_T the data of K , Λ , ϕ and Ω in the log scale are all well reproduced in our study that extends the thermal contribution and includes the shower contribution. The calculated result on the Λ/K ratio rises to a maximum of around 2 at $p_T \approx 4$ GeV/c, arching over the data in linear scale. The production of ϕ and Ω are shown to arise mainly from the recombination of thermal partons, thus exhibiting exponential p_T dependences in agreement with the data. Their ratio, $R_{\Omega/\phi}$, rises linearly to $p_T \approx 4$ GeV/c and develops a maximum at $p_T \approx 5.5$ GeV/c. It is argued that the p_T spectra of ϕ and Ω reveal directly the partonic nature of the thermal source that characterizes quark-gluon plasma. Comments are made on the Ω puzzle due to the simultaneous observation of

both the exponential behavior of the Ω spectrum in p_T and the existence of low- p_T particles associated with Ω as trigger.

1 Introduction

The production of strange particles has always been a subject of great interest in heavy-ion collisions because of their relevance to possible signatures of deconfinement and flavor equilibration [1, 2]. Strangeness enhancement that has been observed at various colliding energies is a phenomenon associated with soft particles in the bulk matter [3, 4]. At high transverse momentum (p_T), on the other hand, the production of jets does not favor strange particles, whose fragmentation functions are suppressed compared to those for non-strange particles. At intermediate p_T range between the two extremes the p_T distribution depends sensitively on both the strangeness content and the production mechanism. It has been shown that in that p_T range the spectra of π and p can be well described by parton recombination [5]. In this paper we study the production of the openly strange particles K , Λ and Ω , as well as the hidden strange hadron ϕ . The aim is to get a broad view of strangeness production at intermediate and high p_T in a unified framework.

The four particles emphasize four different aspects of hadronization: K and Λ involve non-strange quarks, whereas ϕ and Ω do not; K and ϕ are mesons, whereas Λ and Ω are baryons, although ϕ and Λ are comparable in masses. To get all four spectra correctly at all p_T would require a high degree of coordination in the theoretical description. We have already a fairly good description of the production of hadrons in the non-strange sector [5]; however, for the strange sector we must deal with a new set of problems. Gluon conversion

feeds the s quarks in the thermal medium and leads to strangeness enhancement [6]. On the other hand, the production of s quarks at high p_T in jets is suppressed. The interplay between the enhanced thermal s partons and the suppressed shower s partons results in very unusual outcome. Furthermore, how the supply of s quarks is partitioned into various channels of hadrons containing open and hidden strangeness is an aspect of the recombination process that was not encountered in the non-strange sector, but was studied algebraically by quark counting in Refs. [7, 8] without gluon conversion. Our consideration here treats the problem in a much wider scope where the p_T distributions of all four strange particles are investigated.

We shall use the basic recombination formula to compute the p_T distributions of all four particles. The thermal s quark distribution is determined by fitting the low- p_T data of K production. The shower parton distributions (SPD) are known [9]. Thus one can proceed to the calculation of the Λ spectrum essentially without adjustable parameters. In the cases of ϕ and Ω the competition for multiple strange quarks to form such high mass states would lead to suppression. Moreover, since the s quarks from the showers are suppressed compared to non-strange shower partons, ϕ and Ω produced at large p_T do not benefit from hard scattering as much as K and Λ do, for which light shower partons can contribute. The consequence is that the thermal partons play a dominant role — to the extent that the production of ϕ and Ω provides a window to look into the thermal nature of the quark-gluon plasma before hadronization. All these problems will be examined quantitatively in this paper.

2 Formulation of the Problem

We shall assume that all hadrons produced in heavy-ion collisions are formed by recombination of quarks and/or antiquarks, the original formulation of which is given in [10, 11] for pp collisions. In recent years the recombination model has been extensively studied by many groups [12, 13, 14, 5] with great success in reproducing the p_T spectra in the intermediate p_T region of Au+Au collisions. In our 1D description of the recombination process the invariant inclusive distribution of a produced meson with momentum p is

$$p^0 \frac{dN_M}{dp} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} F_{q\bar{q}'}(p_1, p_2) R_M(p_1, p_2, p), \quad (1)$$

and for a produced baryon

$$p^0 \frac{dN_B}{dp} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} \frac{dp_3}{p_3} F_{qq'q''}(p_1, p_2, p_3) R_B(p_1, p_2, p_3, p). \quad (2)$$

The properties of the medium created by the collisions are imbedded in the joint quark distributions $F_{q\bar{q}'}$ and $F_{qq'q''}$. The recombination functions (RFs) R_M and R_B depend on the hadron structure of the particle produced, but for a high mass hadron the normalization can in addition be influenced by the competition among possible channels. In the valon model description of hadron structure [11, 15], the RFs are

$$R_M(p_1, p_2, p) = g_M y_1 y_2 G_M(y_1, y_2), \quad (3)$$

$$R_B(p_1, p_2, p_3, p) = g_B y_1 y_2 y_3 G_B(y_1, y_2, y_3), \quad (4)$$

where $y_i = p_i/p$, and g_M and g_B are statistical factors. G_M and G_B are the non-invariant probability densities of finding the valons with momentum fractions y_i in a meson and a baryon, respectively. Equations (1) and (2) apply for the produced hadron having any

momentum \vec{p} . We consider \vec{p} only in the transverse plane, and write p_T as p so that $dN/p_T dp_T$ becomes $(pp^0)^{-1}$ times the right-hand sides of Eqs. (1) and (2).

The wave function $G(y_i)$ in terms of the momentum fractions of the valons cannot be probed for K, ϕ, Λ , and Ω , as one can for proton. However, we can make reasonable estimates. For K and Λ , there is a mixture of strange and non-strange constituents with different masses, so the corresponding momentum fractions are different. The wave function of K has been considered before [16]; it has the form

$$G_K(y_1, y_2) = \frac{1}{B(a+1, b+1)} y_1^a y_2^b \delta(y_1 + y_2 - 1). \quad (5)$$

The ratio of the average momentum fractions \bar{y}_1 and \bar{y}_2 of the u and s type valons, respectively, should be roughly the ratio of their masses $m_U/m_S \approx 2/3$. That puts a constraint on the parameters a and b , which is $b = (3a + 1)/2$. Phenomenological analysis of the process $K^+ + p \rightarrow \pi^+ + X$ in the valon model then results in $a = 1$ and $b = 2$ [16]. For the hyperon Λ the wave function can be written in the form [6]

$$G_\Lambda(y_1, y_2, y_3) = \frac{1}{B(\alpha+1, \alpha+\beta+2)B(\alpha+1, \beta+1)} (y_1 y_2)^\alpha y_3^\beta \delta(y_1 + y_2 + y_3 - 1), \quad (6)$$

where y_1 and y_2 refer to the non-strange valon, and y_3 to the strange valon. The ratio of the average momentum fractions \bar{y}_1/\bar{y}_3 is $(\alpha+1)/(\beta+1)$, which yields a similar constraint: $\beta = (3\alpha + 1)/2$. We suppose that their values are roughly the same as for proton [15], so they shall be set at $\alpha = 1$ and $\beta = 2$.

For ϕ and Ω only one type of valon is involved, so their valon distributions have the simple symmetric forms

$$G_\phi(y_1, y_2) = [B(c+1, c+1)]^{-1} (y_1 y_2)^c \delta(y_1 + y_2 - 1), \quad (7)$$

$$G_\Omega(y_1, y_2, y_3) = [B(\gamma+1, \gamma+1)B(\gamma+1, 2\gamma+2)]^{-1} (y_1 y_2 y_3)^\gamma \delta(y_1 + y_2 + y_3 - 1). \quad (8)$$

Since the masses of those two particles are nearly at the thresholds of the sums of the constituent quark masses, loose binding means narrow wave functions in the momentum space. We shall consider two cases: (a) $c = \gamma = 5$, and (b) $c = \gamma = 4$. For case (a) or larger c and γ , the distributions in Eqs. (7) and (8) are narrow enough so that they are not too far from the δ -function approximations, i.e.,

$$G_\phi(y_1, y_2) = \delta(y_1 - 1/2) \delta(y_2 - 1/2), \quad (9)$$

$$G_\Omega(y_1, y_2, y_3) = \delta(y_1 - 1/3) \delta(y_2 - 1/3) \delta(y_3 - 1/3). \quad (10)$$

To calculate the p_T distributions, we start with the production of K_s^0 , for which we consider the $d\bar{s}$ and $s\bar{d}$ contributions to $F_{q\bar{q}'}$ and write

$$F_{d\bar{s}, s\bar{d}} = \mathcal{T}\mathcal{T}_s + \mathcal{T}_s(\mathcal{S}_d + \mathcal{S}_{\bar{d}})/2 + \mathcal{T}\mathcal{S}_s + \{\mathcal{S}\mathcal{S}_s\}, \quad (11)$$

where a sum over all relevant quark species is implied when not indicated explicitly. The thermal and shower parton distributions of the light quarks are, respectively, [5]

$$\mathcal{T}(p_1) = p_1 \frac{dN_q^{\text{th}}}{dp_1} = C p_1 \exp(-p_1/T), \quad (12)$$

$$\mathcal{S}(p_2) = \xi \sum_i \int_{k_0}^{\infty} dk k f_i(k) S_i(p_2/k). \quad (13)$$

The parameters C and T have been determined in [5]:

$$C = 23.2 \text{ GeV}^{-1}, \quad T = 0.317 \text{ GeV}. \quad (14)$$

S_i is the SPD for a light quark in a shower initiated by a hard parton i , $f_i(k)$ is the transverse-momentum (k) distribution of hard parton i at midrapidity in central Au+Au collisions, and ξ is the average fraction of hard partons that can emerge from the dense medium to hadronize.

As in [5], $f_i(k)$ is taken from Ref. [17], k_0 is set at 3 GeV/c, and ξ is found to be 0.07. For the strange quarks the corresponding thermal and shower parton distributions are

$$\mathcal{T}_s(p_1) = p_1 \frac{dN_s^{\text{th}}}{dp_1} = C_s p_1 \exp(-p_1/T_s), \quad (15)$$

$$\mathcal{S}_s(p_2) = \xi \sum_i \int_{k_0}^{\infty} dk k f_i(k) S_i^s(p_2/k), \quad (16)$$

where C_s and T_s are now new parameters. The SPDs S_i^s are known from [9] and cannot be altered. Indeed, S_i and S_i^s are so well determined from the meson fragmentation functions (FFs) that we have recently been able to calculate the baryon FFs from them in agreement with data [18], thus solidifying the validity of our approach to fragmentation in the framework of recombination. The thermal s quark distribution in Eq. (15) is determined by fitting the low- p_T data on K_s^0 production. Since K^* decays totally into πK , we have $g_K = 1$.

The last term of Eq. (11) symbolizes

$$\{\mathcal{SS}_s\} = \xi \sum_i \int_{k_0}^{\infty} dk k f_i(k) \left[\left\{ S_i^d \left(\frac{p_1}{k} \right), S_i^{\bar{s}} \left(\frac{p_2}{k-p_1} \right) \right\} + \left\{ S_i^{\bar{d}} \left(\frac{p_1}{k} \right), S_i^s \left(\frac{p_2}{k-p_1} \right) \right\} \right] / 2, \quad (17)$$

where $\{\dots, \dots\}$ on the RHS represents symmetrization of p_1 and p_2 . The two terms in the square brackets are not the same because of the valence quark contribution to the d -initiated jet. Despite the appearance of the product form on the LHS, there is only one integral over k because both shower partons belong to the same jet initiated by one hard parton i . Since we sum i over $u, d, s, \bar{u}, \bar{d}, \bar{s}$ and g , Eq. (17) contains 28 terms. However, when they are combined with the RF, they become the FF $D_i^{K_s^0}(p/k)$ [5].

For Λ production we need

$$F_{uds} = \mathcal{T}\mathcal{T}\mathcal{T}_s + \mathcal{T}\mathcal{T}_s\mathcal{S} + \mathcal{T}\mathcal{T}\mathcal{S}_s + \mathcal{T}_s\{\mathcal{SS}\} + \mathcal{T}\{\mathcal{SS}_s\} + \{\mathcal{SSS}_s\}, \quad (18)$$

where the last term involves the symmetrization of all three shower partons in the same jet.

Clearly, there are now many more terms for F_{uds} . We shall find that up to $p_T \approx 4$ GeV/c, the relative importance of each of the six terms in Eq. (18) diminishes in the order they appear on the RHS. Nevertheless, they all have to be calculated in order to determine the emergence of certain terms, as p_T is increased. For the RF of Λ the statistical factor g_Λ is 1/4. With the parameter α in the Λ wave function expressed in Eq. (6) set at 1 to simulate the proton, there are no adjustable parameters in this Λ production problem.

For ϕ and Ω the p_T distributions can be written out explicitly if the naively simple forms in Eqs. (9) and (10) for their RFs are used. They are

$$\frac{dN_\phi}{pd\mu} = \frac{g_\phi}{pp_0} F_{s\bar{s}}(p/2, p/2), \quad (19)$$

$$\frac{dN_\Omega}{pd\mu} = \frac{g_\Omega}{pp_0} F_{sss}(p/3, p/3, p/3), \quad (20)$$

where

$$F_{s\bar{s}} = \mathcal{T}_s \mathcal{T}_{\bar{s}} + \mathcal{T}_s \mathcal{S}_{\bar{s}} + \{\mathcal{S}_s \mathcal{S}_{\bar{s}}\}, \quad (21)$$

$$F_{sss} = \mathcal{T}_s \mathcal{T}_s \mathcal{T}_s + \mathcal{T}_s \mathcal{T}_s \mathcal{S}_s + \mathcal{T}_s \{\mathcal{S}_s \mathcal{S}_s\} + \{\mathcal{S}_s \mathcal{S}_s \mathcal{S}_s\}. \quad (22)$$

In our calculation we shall, however, use the RFs given in Eqs. (7) and (8) and consider the two cases given below those equations. We allow the normalization factors g_ϕ and g_Ω to be adjustable in order to account for the medium effect on the recombination of $s\bar{s}$ and sss . Because of the limited supply of s quarks and the abundance of the light quarks in the vicinity, it is expected that the formation of the multi-strange particles at higher masses would be suppressed. Without a principle from outside the recombination model, there is no way to determine the suppression factors. In the following we vary g_ϕ and g_Ω as free parameters to fit the normalizations of the corresponding spectra. Current data on the spectra of strange particles extend to p_T as high as 6 GeV/c [18]-[25].

3 Results

We first show the result of our calculation for K_s^0 production. In Fig. 1 is shown the contributions from the three components indicated in the figure. The thermal-shower component includes both the $\mathcal{T}_s\mathcal{S}$ and $\mathcal{T}\mathcal{S}_s$ subcomponents, although the latter subcomponent is much smaller because the shower s quark is suppressed. The contribution from $\mathcal{T}_s\mathcal{S}$ is more important because thermal s quarks are not negligible, as evidenced by the $\mathcal{T}\mathcal{T}_s$ component that is dominant for $p_T < 3$ GeV/c. The $\{\mathcal{S}\mathcal{S}_s\}$ component does not become important until $p_T > 8$ GeV/c.

In fitting the low- p_T region for $p_T < 2$ GeV/c we use

$$C_s = 13.9 \text{ GeV}^{-1}, \quad T_s = 0.33 \text{ GeV}. \quad (23)$$

This value of T_s is slightly higher than $T = 0.317$ GeV for light quarks. Since the low p_T phenomenology includes the flow effect, which we do not separately put in, that small difference in the inverse slopes is sensible in view of the mass difference involved. Note that it is because of the importance of the contribution of the thermal-shower recombination for $p_T > 3$ GeV/c that the p_T distribution bends up from the exponential behavior to agree with the data [23].

Having determined C_s and T_s , we can now proceed to the calculation of Λ production without adjusting any parameters. There are, however, two cases to consider that are related to the valence quarks in the showers. The question is whether the leading parton is likely to form a leading meson in a jet or a baryon with higher mass, remembering that there is only one valence quark in a quark-initiated shower. We calculate the p_T distributions of Λ for the two cases, where (a) only the sea quarks in the showers are used for the formation of Λ ,

and (b) all contributions including all valence quarks are included. The results are shown in Fig. 2(a) and (b), respectively. There is a small but perceptible difference between the two cases for $p_T > 4$ GeV/c. The inclusion of valence quarks in (b) naturally has the effect of increasing the yield at high p_T .

In Fig. 2 we first note that the recombination of three thermal partons (TTT) is dominant up to about 4 GeV/c, where the TTS contribution becomes more important at higher p_T . The TSS component is unimportant below 6 GeV/c, and SSS is even less important. Fig. 2(a) gives a more satisfactory reproduction of the data [23] than Fig. 2(b). It implies that the valence quarks that have larger momentum fractions in a jet are mainly in the mode of formation of mesons instead of hyperons. Gluon jets make the dominant contribution to the shower partons that form the Λ .

With the calculated p_T distributions of K_s^0 and Λ at hand, we can take their ratio and compare it with the data on Λ/K_s^0 [22, 23]. Since the latter is shown in linear scale, it is far more sensitive to the details of the p_T distributions than the spectra themselves plotted in log scale. What is shown by the solid line in Fig. 3 is the result on the Λ/K_s^0 ratio using the p_T distributions shown in Figs. 1 and 2(a). Our calculated result in Fig. 3 does not reproduce the data at large p_T , although they agree well for $p_T < 2$ GeV/c. The solid line has the right structure of a peak reaching almost as high as 2. The disagreement with data is an amplification of the small discrepancies between theory and experiment in Figs. 1 and 2(a), where our calculated distribution for K_s^0 in the region $4 < p_T < 6$ GeV/c is slightly lower than the data, but for Λ it is slightly higher than the data. That intermediate p_T region is where the shower contributions become important. Evidently, our model for the production of such strange particles is not good enough to yield better than 30% accuracy.

When the shower parton contribution is not strong, it is necessary to rely on the accuracy of the thermal parton distribution extrapolated to very high p_T , higher than can perhaps be justified with the simple exponential formula used. Moreover, it is likely that hadronization into different strange hadronic channels may not be independent, so the partition problem in the strange sector may have to be taken into account.

For the production of ϕ and Ω we have done the calculation for both cases (a) $c = \gamma = 5$ and (b) $c = \gamma = 4$ for the valon distributions given in Eqs. (7) and (8) that are used in the RFs in Eqs. (3) and (4). For clarity we show only the results for case (a) in Figs. 4 and 5, since the other case will be shown to be ruled out by the Ω/ϕ ratio. If we ignore all but the first terms on the RHS of Eqs. (21) and (22), we would have only the thermal contributions, which from (19), (20) and (15) give¹

$$\frac{dN_\phi}{pdः} = g_\phi C_s^2 \frac{p}{4p_0} e^{-p/T_s}, \quad (24)$$

$$\frac{dN_\Omega}{pdः} = g_\Omega C_s^3 \frac{p^2}{27p_0} e^{-p/T_s}, \quad (25)$$

where C_s and T_s are as given in Eq. (23). The results from using $c = \gamma = 5$ in Eqs. (7) and (8) are similar, but cannot be expressed in simple analytic form as in Eqs. (24) and (25); they are shown by the dashed lines in Figs. 4 and 5. Being from the thermal contributions only, they are nearly exponential for $p_T > 2$ GeV/c. The other terms in Eqs. (21) and (22) involving shower partons give rise to contributions shown by the other lines in those figures, which are lower. Their sums represented by the solid lines differ only slightly from the dashed lines. It is clear then from Figs. 4 and 5 that the p_T distributions of both ϕ

¹These simple formulas are the result of using the δ -function approximations of the wave functions in Eqs. (9) and (10) for the recombination functions.

and Ω are dominated by the recombination of thermal partons (\mathcal{T}_s) in the regions where data are available [21, 24, 25]. The contribution of thermal-shower recombination ($\mathcal{T}_s \mathcal{S}_s$) to ϕ production does not exceed that from $\mathcal{T}_s \mathcal{T}_s$ until $p_T > 6$ GeV/c. For Ω the cross-over is above 8 GeV/c, not shown in Fig. 5. The production of shower s quark is suppressed, but it is enough to make a few percentage contribution at the high end of p_T where data exist.² The overall normalizations of the distributions are fitted by adjusting the values of g_ϕ and g_Ω to be

$$g_\phi = 0.34, \quad g_\Omega = 0.012. \quad (26)$$

They represent the degree of suppression of the rate of recombination of an s quark with an \bar{s} (to form ϕ) and two other s quarks (to form Ω) in the environment of light quarks that present competing channels for the formation of kaons and hyperons. The phenomenon is similar to that in the Λ production where the leading s quark prefers to form K rather than Λ , as shown in the two parts of Fig. 2.

To calculate the ratio $R_{\Omega/\phi}$ we can start with the simplest by using Eqs. (24) and (25) and get

$$R_{\Omega/\phi}^{\text{th}}(p) = \frac{4g_\Omega C_s}{27g_\phi} p, \quad (27)$$

which is linearly rising. However, that is for thermal-parton recombination with δ -function RFs. For case (a) RFs with $c = \gamma = 5$, the result for thermal contribution only is shown by the dashed line in Fig. 6, which is the ratio of the dashed lines in Figs. 4 and 5, and is approximately linearly rising. When all terms are included, the ratio of the solid lines in

²This result differs from the earlier one in [26], where a number of approximations were made, and a smaller values of ξ was used by mistake.

Figs. 4 and 5 results in the solid line in Fig. 6. There is a definitive bending down of the ratio for $p_T > 5$ GeV/c, although the solid lines in Fig. 4 and 5 deviate only slightly from the dashed lines in the log scale. The linear scale in which the ratio is shown magnifies the deviation arising from the contributions of the shower partons. The solid line exhibits the trend of the data that departs from linearity at $p_T \approx 4$ GeV/c [25]; however, our model calculation gives a peak at $p_T \approx 5$ GeV/c which is slightly higher than the data, and with the maximum at $R_{\Omega/\phi} \approx 0.25$. The decrease of Ω/ϕ at high p_T is due to the increase of the ϕ spectrum that is lifted up from the exponential behavior by the contribution from thermal-shower recombination. That upward bending of the ϕ spectrum occurs earlier in p_T than that of Ω , with the consequence that Ω/ϕ decreases for $p_T \geq 5$ GeV/c. In Fig. 6 we also show in dashed-dotted line the Ω/ϕ ratio for $c = \gamma = 4$ in the wave function of ϕ and Ω [see Eqs. (7) and (8)], corresponding to broader widths in the momentum-fraction space. The result is far from the data and should be discarded from further consideration. It does confirm our earlier statement that narrow width in the momentum space is expected due to the weak binding of constituent quarks in ϕ and Ω .

4 Discussion

In the approach to the hadronization problem that we have adopted there are certain properties that we cannot change, while there are others that we can determine only by fitting the data. The former involve the hard partons and their shower parton distributions. Of course, they can be improved by going to higher order calculations, which we rule out for the present consideration. The latter involve the soft thermal partons, for which several

parameters have been used for non-strange and strange quarks. Since our aim has never been to model the soft component, it does not matter how many parameters have been used to reproduce the low p_T behavior. Our aim has been to understand strange particle production at intermediate and high p_T , and we have found some valuable information to provide significant insight into the strange sector. The recombination model has been effective in illuminating the physics involved.

From K_s^0 and Λ spectra we have seen how the deviation from the exponential behavior that describes the thermal components can be understood as being due to the emergence of the shower contribution arising from jets. It happens at around $p_T \approx 4$ GeV/c. Those are strange hadrons containing light quarks, which are easier to produce at high p_T than the strange quarks that are suppressed. The thermal source provides the s quarks for recombination. The Λ/K ratio has a maximum at $p_T \approx 4$ GeV/c, a bit higher than the location of the peak in the data [23]. The cause of the decrease of the ratio is the relative ease of K over Λ in acquiring a boost in yield by thermal-shower recombination at high p_T . Quantitatively, we do not expect better than 30% accuracy in the spectra themselves, since lowest order pQCD was used in the calculation of hard scattering, and the virtuality of the shower partons is not changed according to the p_T of the fragmenting hard partons. Despite that limitation the fact that the spectra can be reproduced over such a wide range of yield for p_T up to 6 GeV/c (a span of 5 orders of magnitude) is sufficient to be regarded as support for the validity of the recombination model used.

In the case of ϕ and Ω the absence of light quarks in them deprives them of the light shower partons at high p_T , so their productions are dominated by the thermal strange-quark recombination. The contribution from hard parton scattering is negligible unless p_T is large.

The small upward bend of the ϕ and Ω spectra above straight-line behaviors in the log plots (i.e., exponential) results in the Ω/ϕ ratio to bend down above $p_T \approx 5$ GeV/c. Ω is harder to be lifted up by shower s quark than ϕ because there are two thermal s quarks instead of one, given that shower s partons are suppressed in the first place.

The significance of the Ω/ϕ ratio in Fig. 6 is not so much the bending down of the solid line at high p_T as the rising of the dashed line at intermediate p_T in agreement with the data. That rising behavior can be seen clearly in the simple analytic expressions in Eqs. (24) and (25), from which one gets the ratio to be proportional to p (which is abbreviation for p_T in Fig. 6). Although those expressions are simplified approximations, they exhibit two features: (a) the extra factor of p in Eq. (25) compared to (24) is due to the difference in the RFs of the baryon versus meson shown in Eqs. (4) and (3), respectively, and (b) the more important aspect of those two expressions is the common exponential factors that are cancelled in the ratio — those factors are dynamical in origin, while the prefactors are kinematical. The fact that the dashed line in Fig. 6 well describes the data up to $p_T \approx 4$ GeV/c implies that both ϕ and Ω have the same dynamical origin of thermal partons, which are assumed to have exponential behavior given in Eq. (15). The surprise is the validity of that exponential form out to $p \approx 2$ GeV/c for ϕ observed at $p_T \approx 4$ GeV/c, remembering that T_s is only 0.33 GeV. Thus we have a very robust system of thermal partons consisting of not only the light quarks but also the strange quarks. That is the main characteristic of quark-gluon plasma [1, 2]. It takes the production of ϕ and Ω to reveal cleanly this thermal source because their exponential behavior at intermediate p_T is not covered up by the contamination of shower partons from hard scattering, as is the case with other mesons and baryons. In that sense ϕ and Ω serve as windows through which one can observe directly the properties of the partonic

source.

The discussion above concerns the shapes of the p_T distributions of ϕ and Ω . The normalizations have been adjusted to fit the data by giving the parameters g_ϕ and g_Ω the values shown in Eq. (26). The fact that they are less than 1 implies suppression. We interpret that as being due to the competition for s quarks in the environment of light quarks during hadronization. Evidently, it is less likely for an s to find an \bar{s} to form ϕ than a \bar{u} or \bar{d} to form K ; it is even more difficult to find two other s quarks to form Ω . To study the constraints arising from competing channels is outside of the scope of this paper, since our emphasis has been on the p_T dependence of the strange hadron production. The values of g_ϕ and g_Ω can, however, be useful at a later point when the competition problem is considered.

The phenomenological fact that the p_T distribution of Ω is essentially exponential up to $p_T \approx 6$ GeV/c leads one to conclude, even without the benefit of our model calculation, that Ω is produced from the thermal source. It is then natural to predict that any particle produced in association with Ω must also be from the same thermal source, and hence indistinguishable from the background. Such a prediction was, in fact, made in the unpublished version of this work [26], which stimulated an experimental search for the partners of Ω above background. The result of that study was reported at Quark Matter 2006, indicating that unidentified charged particles were found on the near side of the $\Delta\phi$ distribution in association with Ω as trigger for $2.5 < p_T^{\text{trig}} < 4.5$ GeV/c and $1.5 < p_T^{\text{assoc}} < p_T^{\text{trig}}$ [27]. Those are rather low values of p_T^{trig} and p_T^{assoc} , lower than what can unambiguously give rise to the usual jet structure. For $p_T^{\text{trig}} < 4.5$ GeV/c we see in Fig. 5 that the contribution from thermal-thermal-shower recombination is minuscule compared to that of thermal partons only. Thus there are no apparent jets to account for the associated particles. This dilemma,

called the Ω puzzle, was addressed at Quark Matter 2006 and resolved conceptually by the notion of phantom jet [28]. Without entering into the details of the possible resolution, we mention here only the essence of the idea. It is conjectured that both the Ω and its associated particles are produced from the ridge induced by jets, the nature of which has been studied for other triggers [27]. The ridge is an enhanced thermal source, and is itself not jet-like, but without a jet (created by gluon or light quark) there would not be any ridge [29]. A ridge without peak may therefore be regarded as the shadow of a phantom jet. If the associated particles are in the ridge, then they can be observed above the background. Quantitative implementation of this idea remains to be carried out, but probably not until more data become available on ridge characteristics. At present, without $\Delta\eta$ distribution there is no identification of a ridge due to the low statistics in Ω production.

In conclusion, we remark that intermediate p_T physics in the strange sector at RHIC has been substantially illuminated by this study where hadron production up to $p_T \sim 6$ GeV/c can be understood in terms of recombination. Fragmentation is ruled out. Although the calculated results on Λ/K and Ω/ϕ ratios do not agree perfectly with the data on the high end of the p_T range, they represent only less than 30% discrepancies in the spectra themselves that vary over 5 orders of magnitude. The most significant revelation is that a robust thermal parton source is created at RHIC before hadronization.

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Figure Captions

Fig. 1. Transverse momentum distribution of K_s^0 in central Au+Au collisions. Data are from [23]. The solid line is the sum of the three contributions: $\mathcal{T}\mathcal{T}$ (dashed line), $\mathcal{T}\mathcal{S}$ (dashed-dot line), $\mathcal{S}\mathcal{S}$ (dotted line).

Fig. 2. Transverse momentum distribution of Λ in central Au+Au collisions. Data are from [23]. The heavy solid line is the sum of the four contributions: $\mathcal{T}\mathcal{T}\mathcal{T}$ (dashed line), $\mathcal{T}\mathcal{T}\mathcal{S}$ (dashed-dotted line), $\mathcal{T}\mathcal{S}\mathcal{S}$ (dotted line), $\mathcal{S}\mathcal{S}\mathcal{S}$ (light solid line). (a) no valence quarks are included; (b) valence quarks are included.

Fig. 3. The ratio of Λ to K_s^0 . Data are from [22, 23]. The solid line is from Fig. 1 and Fig. 2 (a).

Fig. 4. Transverse momentum distribution of ϕ in central Au+Au collisions. Data are from [19, 20]. The solid line is the sum of the three contributions: $\mathcal{T}\mathcal{T}$ (dashed line), $\mathcal{T}\mathcal{S}$ (dashed-dot line), $\mathcal{S}\mathcal{S}$ (dotted line).

Fig. 5. Transverse momentum distribution of Ω in central Au+Au collisions. Data are from [21, 24, 25]. The heavy solid line is the sum of the four contributions: $\mathcal{T}\mathcal{T}\mathcal{T}$ (dashed line), $\mathcal{T}\mathcal{T}\mathcal{S}$ (dashed-dotted line), $\mathcal{T}\mathcal{S}\mathcal{S}$ (light solid line), $\mathcal{S}\mathcal{S}\mathcal{S}$ (dotted line).

Fig. 6. The ratio of Ω to ϕ . Data are from [24, 25]. The dashed line is for $c = \gamma = 5$ in the RF and for thermal parton recombination only. The solid line is for $c = \gamma = 5$ and includes all components of recombination. The dashed-dotted line is for $c = \gamma = 4$ with all terms included.











